DISPOSABLE AIR-BURSTING DETONATORS AS AN ALTERNATIVE ON-CHIP POWER SOURCE

Chien-Chong Hong, Jin-Woo Choi, and Chong H. Ahn

Microsystems and BioMEMS Lab
Department of Electrical and Computer Engineering and Computer Science
University of Cincinnati
Cincinnati, OH 45221-0030, USA

ABSTRACT

A new concept of disposable air-bursting detonator as an alternative on-chip power source has been proposed, designed, and successfully demonstrated in this paper for disposable lab-on-a-chips or biochips. In this new disposable air-bursting detonator, a microheater is positioned on the thermoplastic membrane attached over a pressurized chamber. By applying an electrical pulse into the microheater, the thermoplastic membrane can be broken and then the pressurized air will be detonated to drive liquid samples through microchannels. Both air pressure and detonating temperature are adjustable to get desired driving pressure responses. Dynamic pressure response of the fabricated air-bursting detonator has been simulated and experimentally characterized. Due to its compact structure and fast response, this detonator will be a promising alternative power source to drive fluid samples in disposable lab-on-a-chips or portable clinical diagnostic kits.

INTRODUCTION

Micropumps are the most common devices to produce and control pressure for microfluidic systems. There have been many reports for the development of active micropumps using electrostatic, electromagnetic, thermo-pneumatic, electrohydrodynamic or magnetohydrodynamic actuation [1-6]. However, the active micropumps usually require on-line electrical power or off-line batteries. For disposable microfluidic-based biochips or biochemical detection systems, however, the active micropumps should be integrated with disposable batteries, which increases the cost and also involves many technical difficulties. So, an alternative new power source to the battery is desirable for the disposable biochips or clinical diagnostic kits, combining with passive-type microfluidic components.

Micro gas-turbine engine could be a possible option to provide fast-response pressure source for driving liquid in a microchannel, but they are not suitable for the microfluidic biochips due to its environmental noises such as humidity, shock, and vibration [7-9]. Other option could be a cold-gas microthruster, which consists of a nozzle structure and a heater to produce pressurized gas output by heating gas. However, it also needs high power consumption in heating up gas to generate enough pressure [10]. Although mass-production would be possible with the gas microthruster, this approach is still cost-ineffective for disposable biochips or biological analysis systems.

In this work, a novel concept for an alternative on-chip power source has been proposed and realized to address the problems from the disposable microfluidic biochips and biological analysis systems. Gas or air pressurized in a micro chamber can be utilized as a power source to control liquid flow on the disposable chips. The gas or air can be stored in the chamber and then detonated as shown in Figure 1 (a).

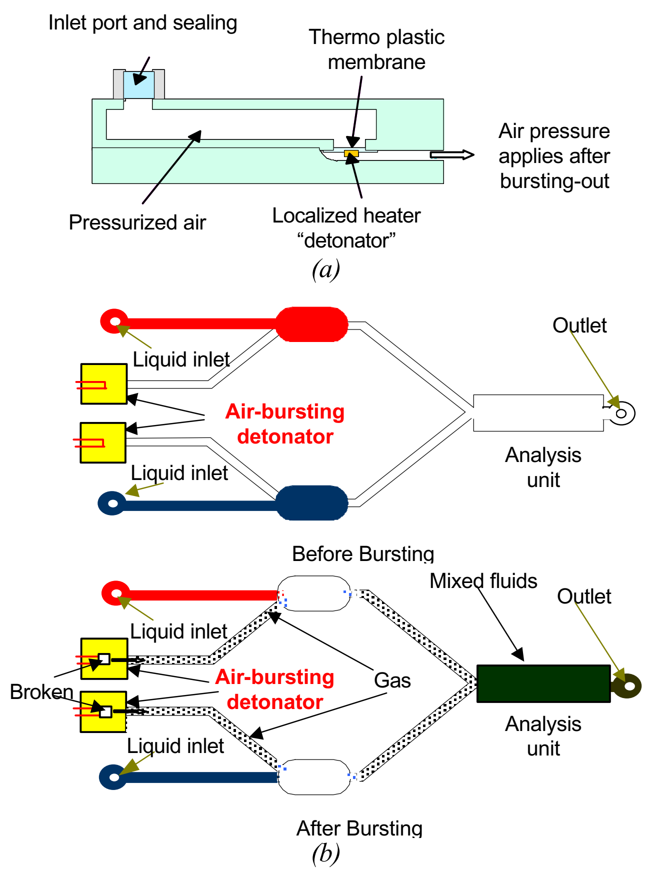

Figure 1. *Schematic illustrations of the disposable air-bursting detonator as an alternative on-chip power source for disposable biochips: (a) cross-sectional view of the device and (b) driving principle of the air-bursting detonator.*

Figure 1 shows a schematic illustration of the novel disposable air-bursting detonator as an alternative on-chip power source. Pressurized gas, which is compressed and stored in the chamber, produces pressure to drive fluid samples in microchannel upon "triggering" by a so-called detonator that is a microheater. Once an electric power pulse is applied to the microheater, then the heater will rapidly produce localized heat, softening the thermoplastic and increasing thermal stress over the membrane. The thermal stress of the membrane will be increased until the membrane is broken – the detonator then triggers the compressed and stored gas to burst out. After the membrane is broken, the pressurized gas pushes the fluid samples into the microchannel through a broken hole on the membrane. So, low power consumption is guaranteed since only one pulsed power is used to burst the pressurized gas, and the detonator can be easily fabricated with the disposable plastic biochips.

DESIGN AND SIMULATION

In the device shown in Figure 1 (a), the detonator has its own pressure-discharge characteristics, depending on the flow resistance of detonating hole and the dimension of fluidic channel. The characteristics of this microfluidic "*battery*" can also be tailored by designing the microheater to produce different sizes of detonating holes, which results in different gas flow resistances and pressure drops.

Dynamic thermo-mechanical simulation was performed by CFD-ACE+ to investigate the temperature profile and thermal stress on the microheater and membrane as shown in Figure 2. SU-8 was chosen as the membrane material and a mender-type microheater structure was employed at the edge of the membrane. The stress of the membrane was attained from the combination of thermal stress and the stress caused by the pressurized gas.

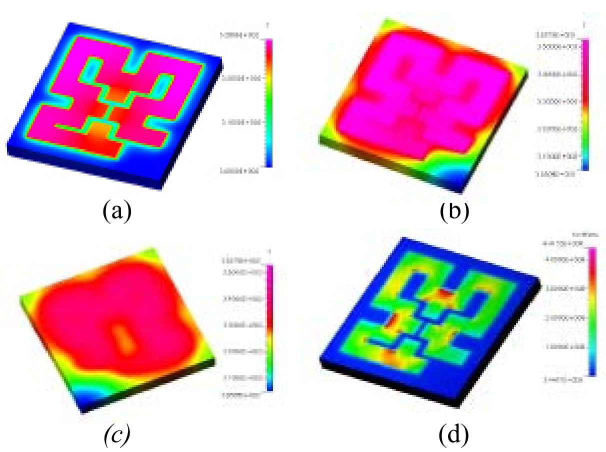

Figure 2. *Dynamic thermo-mechanical simulation using CFD-ACE+ package: (a) temperature profile on the top surface at 10 ms; (b) temperature profile on the top surface at 100 ms; (c) temperature profile on the bottom surface at 100 ms; and (d) thermal stress on the membrane at 100 ms.*

For simulation, material properties such as conductivity and specific heat were assumed to have constant values for simulation and external convection boundary conditions were applied to all boundary surfaces considering heat dissipation by air convection. Gas pressure was applied on the bottom of the membrane structure. The thermal stress and the stress caused by the pressure were combined together after the simulation. The simulation results showed that temperature at the bottom of the membrane reaches 50 *°C* (the glass transition temperature of not cross-linked SU-8) at 100 *mSec* after triggering by 0.7 *V* of pulsed voltage. According to the viscoelastic theory, the Young's modulus of the polymer will rapidly decrease as the temperature goes above glass transition temperature. Figure 3 shows the temperature history of the heater for different power input. Obviously, lower power input has slower response because of heat capacity of the materials and heat dissipation to air by convection.

From the simulation, the maximum stress on the membrane of exposed SU-8 region was obtained. The membrane is located under the microheater structure. As the stress increases, the membrane will have thermal cracking on the location when the stress is above the ultimate stress (34 *MPa*) [11]. Then, the crack will grow until the membrane is broken due to the increased temperature and applied pressure. For this heater design, it shows that the crack, which occurs on the exposed SU-8, is before the not cross-linked SU-8 reaches the glass transition temperature.

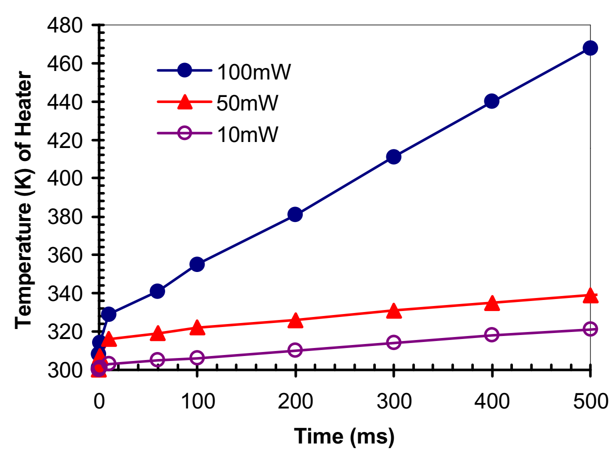

Figure 3. *Dynamic thermal simulation results for different power inputs.*

FABRICATION

To fabricate the detonating membrane, silicon wafer was anisotropically etched in KOH solution from the bottom to form a cavity. After silicon etching, an electroplated microheater of 5 *μm*-thick nickel was fabricated on the top of the silicon wafer. Then, a SU-8 membrane of 50 *μm*-thick was spun on the top of the silicon substrate. The SU-8 membrane was patterned to have exposed region (high glass transition temperature) and un-exposed region (low glass transition temperature). After hard bake, RIE was used to etch the silicon membrane, releasing the SU-8 membrane structure with the microheater as shown in Figure 4.

Using the similar fabrication steps, a pressure chamber to be pressurized was fabricated on silicon substrates, and then a flexible pipette was glued over the inlet of the pressure chamber. Using the pipette, air or gas was pressurized into the chamber. For fluidic tests, the device was integrated with a microchannel by UV-curable epoxy bonding.

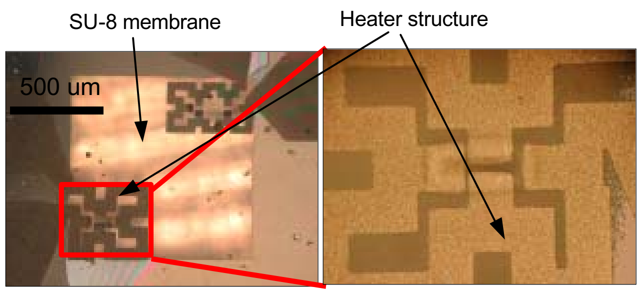

Figure 4. Microphotographs of the fabricated microheater structures.

EXPERIMENTAL RESULTS

To test the detonation capability of the device, an electrical pulse of 0.7 V was applied to the microheater with an input power of 80 μWh. The polymer (SU-8 in this case) membrane was successfully "triggered" to release compressed air through the broken holes, as shown in Figure 5. The developed device functionally worked as a "detonator".

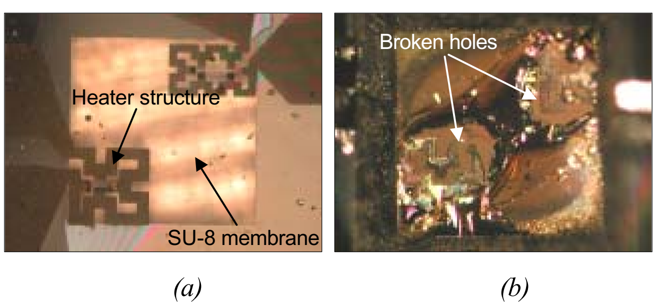

Figure 5. *Microphotographs: (a) before detonation and (b) after detonation with 80 μWh.*

In order to visually observe step-by-step bursting motion, fine powders (spheres of 2 μm in diameter) were scattered and then burst on the device. Air-bursting motions with the fine powers are shown in Figure 6. At a given air pressure in the chamber, the discharge-pressure increase s with the detonating power, since higher detonation power produces bigger holes through the membrane. On the other hand, with higher air pressure in the chamber, the detonator requires lower detonating power consumption, which is desirable for the host instrument with battery operation.

Dynamic pressure response was also measured using the experimental setup shown in Figure 7. The experimental setup includes a CCD image system, a pressure sensor, and a power supply, which are connected to PC for Lab View control and data acquisition.

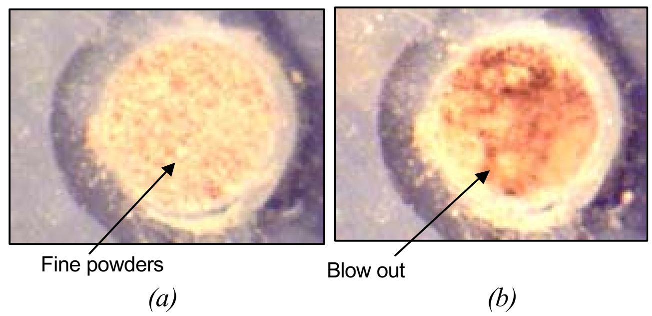

Figure 6. *Air-bursting motions with fine powers at: (a) 0.0 Sec and (b) 0.3 Sec, where the chamber pressure was 4.0 psi and its detonating power was 80 μWh.*

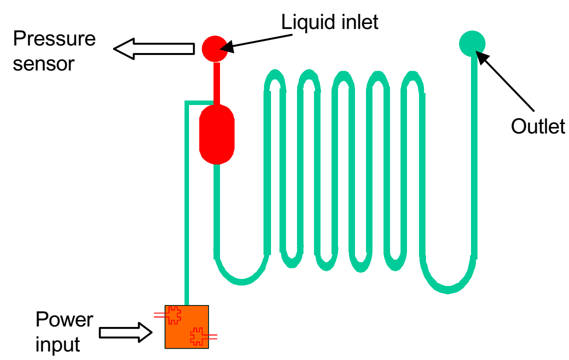

Figure 7. *Experimental setup to measure dynamic pressure response and to record the liquid flow.*

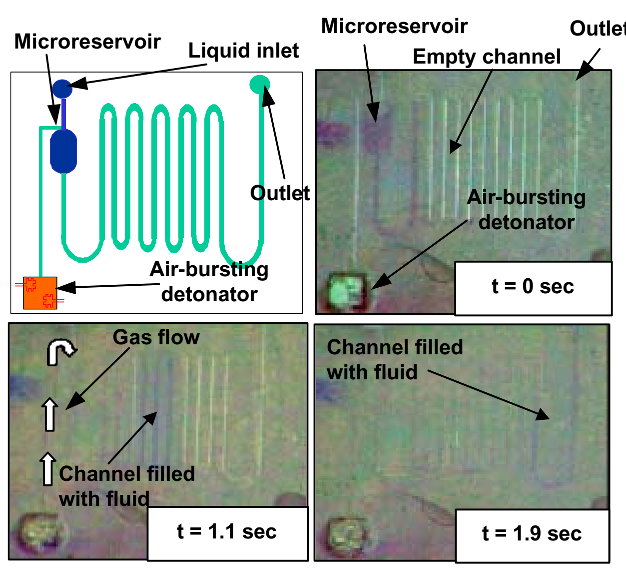

Figure 8. *Flow demonstration of liquid sample at different time steps as an alternative on-chip power source.*

For driving a liquid sample through the device, dyed water was injected into the chamber and then the liquid inlet was sealed. Then, a 2.78 μWh of input power was applied on the heater and 14 *psi* of pressure was applied on the membrane at the same time. After the membrane broken, gas entered the liquid chamber to push the liquid through a long microchannel. The liquid was successfully driven through the microchannel from the pressure chamber as demonstrated in Figure 8.

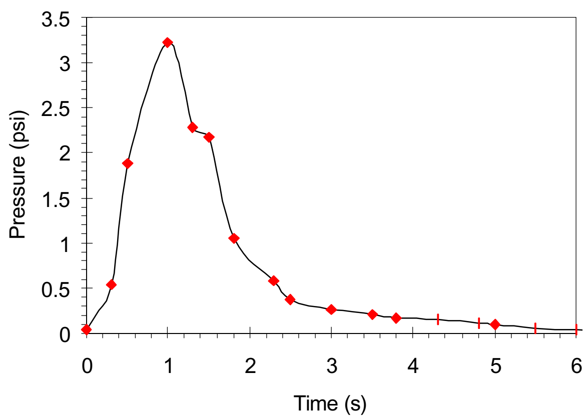

Figure 9. *Experimentally recorded dynamic pressure measurement of the air-bursting detonator.*

The dynamic discharging-pressure curve of the air-bursting detonator was also measured using the pressure sensor during detonating. Due to the limitation of dynamic pressure measurement, the testing pressure was set to 4 *psi* and the detonating power was increased up to 80 μWh. The measured dynamic pressure is drawn in Figure 9, where the maximum discharge-pressure of 3.3 *psi* was attained after 1.0 *Sec* and then the pressure decreased exponentially. What the maximum pressure pulse was attained at 1.0 *Sec* might be caused by that the membrane was broken slowly due to the heat dissipation over the membrane.

CONCLUSION

A new concept of disposable air-bursting detonator as an alternative on-chip power source has been proposed, designed, and successfully demonstrated for disposable microfluidic biochips. Thermomechanical simulation was performed to design an optimized detonator structure. The fabricated device clearly showed air-bursting action after detonation and the dynamic pressure curve was characterized. The novel disposable air-bursting detonator realized in this work showed promising performances in driving liquid samples through the microchannel with a low power consumption. This disposable detonator can be applied for numerous microfluidic-based biological analysis systems, disposable clinical diagnostic kits, or disposable drug delivery platforms.

ACKNOWLEDGEMENT

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